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PROBING NEUTRAL GAUGE BOSON SELF-INTERACTIONS IN ZZ PRODUCTION AT THE TEVATRON

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We present an analysis of ZZ production at the upgraded Fermilab Tevatron for general ZZZ and $ZZ\gamma$ couplings. Achievable limits on these couplings are shown to be a significant improvement over the limits currently obtained by LEP II.

1. Introduction

The Standard Model (SM) of electroweak interactions makes precise predictions for the couplings between gauge bosons due to the non-abelian gauge symmetry of $SU(2)_L \otimes U(1)_Y$. These self-interactions are described by the triple gauge boson (trilinear) WWV , $Z\gamma V$, and ZZV ($V = \gamma, Z$) couplings and the quartic couplings. Vector boson pair production provides a sensitive ground for *direct tests* of the trilinear couplings. Deviations of the couplings from the expected values would indicate the presence of new physics beyond the SM.

To date the SM has passed this rigorous test with no observed deviations from the SM values. The WWV and $Z\gamma V$ couplings have been measured with an accuracy of $\mathcal{O}(10\%)$ at LEP2 and the Tevatron¹. The ZZV couplings, on the other hand, are only loosely constrained at the moment through ZZ production at LEP2². Due to low event rates after branching ratios, or large backgrounds, ZZ production was not observed by the Tevatron experiments in Run I. In Run II of the Tevatron which will begin in 2001, an integrated luminosity of $2 - 15 \text{ fb}^{-1}$ is envisioned, and a sufficient number of ZZ events should be available to commence a detailed investigation of the ZZV couplings. In the following we summarize the results of a recent detailed study³ of the capabilities of future Tevatron experiments to test the ZZV vertices via ZZ production.

2. ZZZ and $ZZ\gamma$ Anomalous Couplings

Two ZZZ couplings, and two $ZZ\gamma$ couplings, are allowed by electromagnetic gauge invariance and Lorentz invariance⁴ for on-shell Z bosons. In the massless fermion

limit, the most general form of the $Z^\alpha(q_1) Z^\beta(q_2) V^\mu(P)$ ($V = Z, \gamma$) vertex function may be written as⁴

$$g_{ZZV} \Gamma_{ZZV}^{\alpha\beta\mu} = e \frac{P^2 - M_V^2}{M_Z^2} \left[i f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + i f_5^V \epsilon^{\mu\alpha\beta\rho} (q_1 - q_2)_\rho \right], \quad (1)$$

where M_Z is the Z -boson mass and e is the proton charge. The overall factor $(P^2 - M_V^2)$ in Eq. (1) is a consequence of Bose symmetry for ZZZ couplings, while it is due to electromagnetic gauge invariance for the $ZZ\gamma$ couplings. All couplings are C odd; CP invariance forbids f_4^V and parity conservation requires that f_5^V vanishes. In the SM, at tree level, $f_4^V = f_5^V = 0$.

S -matrix unitarity restricts the ZZV couplings uniquely to their SM values at asymptotically high energies⁵. This requires that the couplings f_i^V possess a momentum dependence which ensures that the $f_i^V(\hat{s})$ vanish for $\hat{s} \rightarrow \infty$. In order to avoid unphysical results that would violate unitarity, the \hat{s} dependence thus has to be taken into account. To parameterize the \hat{s} dependence of the form factor, we use a generalized dipole form factor, $f_i^V(\hat{s}) = f_{i0}^V / (1 + \hat{s}/\Lambda_{FF}^2)^n$, ($i = 4, 5$), where Λ_{FF} is the form factor scale which is related to the scale of the new physics which is generating the anomalous ZZV couplings. The values of the form factors at low energy, f_{i0}^V , and the power of the form factor, n , are constrained by partial wave unitarity of the inelastic ZZ production amplitude in fermion antifermion annihilation at arbitrary center-of-mass energies³.

3. Signatures of Anomalous ZZV Couplings

Our analysis examines the observable final state signatures, $ZZ \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$, $\ell^+ \ell^- \nu \bar{\nu}$, $\ell^+ \ell^- jj$ ($\ell, \ell_1, \ell_2 = e, \mu$) and $\bar{\nu} \nu jj$. The total cross section for $p\bar{p} \rightarrow ZZ$ at $\sqrt{s} = 2$ TeV, including NLO QCD corrections is approximately 1.5 pb. For an integrated luminosity of 2 fb^{-1} one thus expects a few $ZZ \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$ ($\ell_1, \ell_2 = e, \mu$) events, if realistic lepton p_T and pseudo-rapidity cuts are imposed. Larger event rates are expected for $ZZ \rightarrow \ell^+ \ell^- \bar{\nu} \nu$, $ZZ \rightarrow \ell^+ \ell^- jj$ and $ZZ \rightarrow \bar{\nu} \nu jj$. These channels, however, suffer from non-trivial background contributions.

The effects of anomalous ZZV couplings are enhanced at large energies. A typical signal of nonstandard ZZZ and $ZZ\gamma$ couplings thus will be a broad increase in the ZZ invariant mass distribution, the Z transverse momentum distribution and the p_T distribution of the Z decay leptons.

The number of $ZZ \rightarrow \ell^+ \ell^- \bar{\nu} \nu$ signal events is about a factor 6 larger than the number of $ZZ \rightarrow 4$ leptons events. The two most important backgrounds to $ZZ \rightarrow \ell^+ \ell^- \bar{\nu} \nu$ production are $t\bar{t} \rightarrow W^+ W^- b\bar{b}$ and $W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ production. A jet veto almost completely eliminates the $t\bar{t}$ background. The $W^+ W^-$ background exceeds the ZZ signal cross section for $p_T(e^+ e^-) < 80$ GeV. The $p_T(e^+ e^-)$ distribution of the $W^+ W^-$ background, however, drops much faster than that of the ZZ signal, and, thus, will only marginally affect the sensitivity to ZZV couplings.

The decay modes where one of the two Z bosons decays hadronically have much larger branching fractions than the $ZZ \rightarrow 4$ leptons and the $ZZ \rightarrow \ell^+ \ell^- \bar{\nu} \nu$ chan-

nels, but also much higher backgrounds. The main background sources are QCD $Z + 2$ jet (“ Zjj ”) production and WZ production with $W \rightarrow jj$. In both cases the jj invariant mass is constrained to be near the Z pole. Other potentially dangerous background sources are $t\bar{t}$ and Wjj production. The Wjj background contributes only to the $\bar{\nu}\nu jj$ final state. For $ZZ \rightarrow \ell^+\ell^-jj$, the $t\bar{t} \rightarrow \ell^+\nu_\ell\ell^-\bar{\nu}_\ell b\bar{b}$ background can be reduced by requiring that the missing transverse momentum is $\cancel{p}_T < 20$ GeV. For $ZZ \rightarrow \bar{\nu}\nu jj$, suppression of the $t\bar{t} \rightarrow \ell^+\nu_\ell\ell^-\bar{\nu}_\ell b\bar{b}$ and $W(\rightarrow \ell\nu)jj$ backgrounds is possible by requiring that there are no central high- p_T charged leptons present in the event. The Zjj background is found to be, by far, the largest background. Its size is uniformly about one order of magnitude larger than the SM ZZ signal. It will therefore be very difficult to observe ZZ production in the semi-hadronic channels, if the SM prediction is correct. However, for sufficiently large anomalous ZZV couplings, the ZZ cross section exceeds the background at large transverse momenta. The semi-hadronic channels therefore may still be useful in obtaining limits on the ZZV couplings at the Tevatron.

4. Sensitivity Limits

In order to derive sensitivity limits for anomalous ZZV couplings which one can hope to achieve in Run II, we use the $p_T(\ell^+\ell^-)$ distribution for $ZZ \rightarrow 4$ leptons, $ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$ and $ZZ \rightarrow \ell^+\ell^-jj$. For the $ZZ \rightarrow \bar{\nu}\nu jj$ channel we use the $p_T(jj)$ distribution. Other distributions, such as the ZZ invariant mass distribution (useful only for $ZZ \rightarrow 4$ leptons), or the maximum or minimum transverse momenta of the charged leptons or jets, yield similar results. In deriving our sensitivity limits, we combine channels with electrons and muons in the final state. We calculate 95% confidence level (CL) limits performing a χ^2 test, allowing for a normalization uncertainty of 30% of the SM cross section. The most stringent bounds at Tevatron energies are obtained from $ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$ and $ZZ \rightarrow \bar{\nu}\nu jj$. For $\int \mathcal{L} dt = 2 \text{ fb}^{-1}$, $n = 3$ and $\Lambda_{FF} = 750$ GeV one finds:

$$|f_{40}^Z| < 0.159 \quad -0.184 < f_{50}^Z < 0.162 \quad (2)$$

$$|f_{40}^\gamma| < 0.163 \quad -0.179 < f_{50}^\gamma < 0.170. \quad (3)$$

These bounds improve the present limits from LEP II² by a factor 3 to 6. The limits from the $ZZ \rightarrow \ell^+\ell^-jj$ and $ZZ \rightarrow 4$ leptons channels are about a factor 1.5 and 2 weaker than those from $ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$ and $ZZ \rightarrow \bar{\nu}\nu jj$. Bounds roughly scale with $(\int \mathcal{L} dt)^{1/4}$. At the LHC one will be able to probe ZZV couplings of $\mathcal{O}(10^{-3})$ in magnitude³.

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